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An Optimal State of Charge Feedback Control Strategy for Battery Energy Storage in Hourly Dispatch of PV Sources

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Abstract

The effects of intermittent cloud and changes in temperature cause a randomly fluctuated output of a photovoltaic (PV) system. To mitigate the PV impacts particularly on a weak electricity network, battery energy storage (BES) system is an effective means to smooth out the power fluctuations. Consequently, the net power injected to the electricity grid by PV/BES systems can be dispatched smoothly such as on an hourly basis. This paper presents an improved control strategy for a grid-connected BES for mitigating PV farm output power fluctuations. A feedback controller for state of charge is proposed where the control parameters are optimized using genetic algorithm. In this way, the optimal size for the BES is also determined to hourly dispatch a 1.2 MW PV farm. The effectiveness of the proposed control scheme is evaluated using PSCAD/EMTDC-based simulation.

Keywords: Photovoltaic; renewable energy dispatch; battery energy storage; state of charge; parameter optimization

1. Introduction

Large penetration of intermittent renewable energy (RE) generation sources into the utility grid, such as large-scale PV farms, may introduce adverse effects in the operation of interconnected grids, especially in weak power systems [1]. One of the typical challenges in integration of RE sources is in mitigating the output power fluctuations.

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In general, there are many ways used to mitigate fluctuation of output power from RE sources such as use of dump load and generation curtailment [2]. Recently battery energy storage (BES) has become an effective solution to smooth out the short- and mid-term output power fluctuations of MW level RE sources by dispatching the output on an hourly basis [3, 4, 5]. However, as reported in [3, 4, 5], the use of typical one-week PV and wind data as input seems unreliable if both the control performance and adequate sizing of BES are to be evaluated. Furthermore, BES state of charge (SOC) control scheme developed in [3] for wind farm demonstrated poor dispatching performance as the parameters were not appropriately tuned. This paper presents a new BES control method for hourly dispatch of solar energy sources by using genetic algorithm (GA) for tuning the control parameters. A GA-based multi-objective optimization also determines the appropriate size of BES while achieving a perfect dispatch through the controller.

2. PV power dispatch using BES

Fig 1 illustrates the system configuration and operation of the system under study. As shown in Fig 1, a voltage-sourced converter (VSC) is used to charge/discharge the BES according to the commanded active power (d-axis component) and reactive power (q-axis component) references at the outer control loop. The BES is connected to the point of common connection (PCC) through a coupling transformer, TR1 where the net power injected by the BES, P_{BES} will smooth out the output power fluctuation of PV farm, P_{PV} and dispatch the total power, P_{TOTAL} on an hourly basis to the utility grid. In this case, P_{SET} which is assumed as output from forecasting tool [6], is the input signal for the BES controller. It is an hourly set point curve used as reference for BES charging/discharging operation as detailed in the bottom right figure of Fig 1. The accuracy for P_{SET} is set at 10% RMSE to consider accuracy of hourly radiation forecast up to 90% [3, 4, 5].

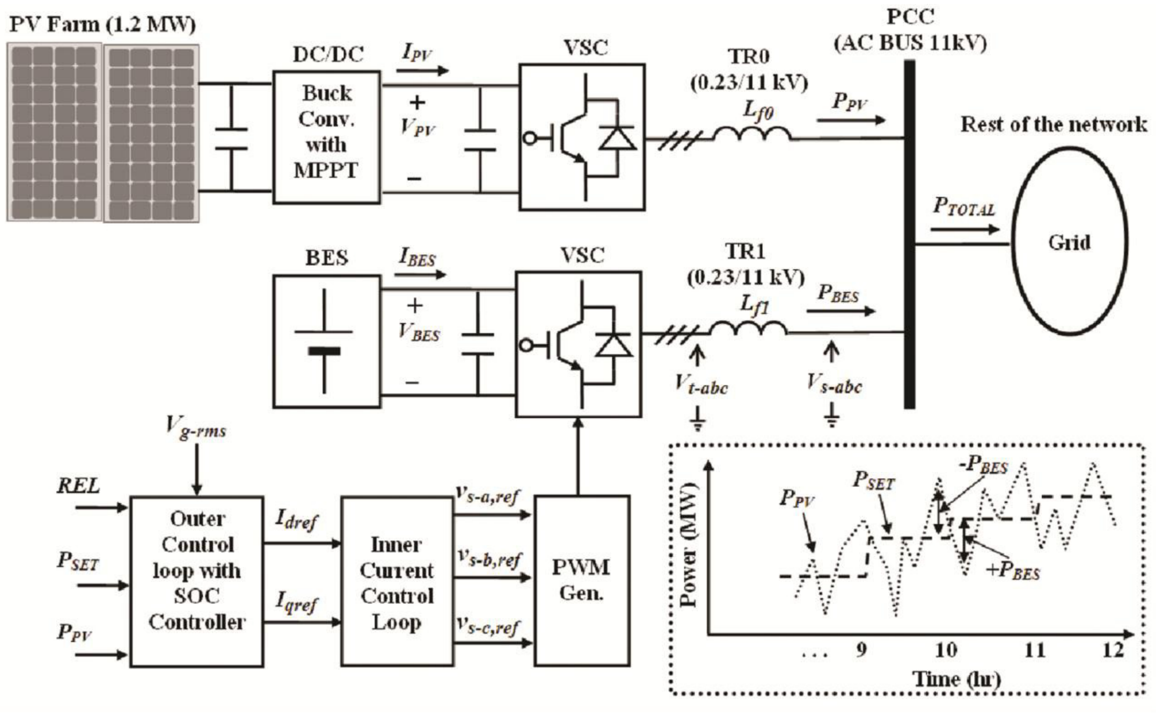


Fig. 1. Grid-connected BES used for hourly dispatch of a PV farm.

3. Modeling and control of BES system

3.1. BES dynamic modeling

A dynamic battery model characterizes the dynamic behavior of the BES, such as the terminal voltage and the SOC. A model of valve-regulated lead acid (VRLA) battery described in [7] is developed, where the terminal voltage, V_{bat}, of individual 12 V battery and the SOC can be calculated as functions of battery current, I_{bat}, as follows:

$$V_{bat} = E_{bat} - R_{in} I_{bat} \tag{1}$$

$$SOC = 100\left(1 - \frac{\int I_{bat}\, dt}{Q}\right) \tag{2}$$

where R_{in} is the total battery internal resistance, Q is the battery capacity, and E_{bat} is the open circuit voltage of the battery modeled with a controlled voltage source. E_{bat} is given by,

$$E_{bat} = E_0 - K\frac{(1-SOC)}{SOC}Q + A\exp(-B(1-SOC)Q) \tag{3}$$

where E_0 represents the battery open circuit voltage between the fully charged voltage and the exponential voltage of the battery discharge curve, K is the polarization voltage, A is the exponential voltage, and B is the exponential capacity. Equation (3) shows that the model accounts for both the normal voltage part and the exponential part represented by the second and third terms, respectively. Following the parameter extraction procedure provided in [7], all model parameters can be extracted from the manufacturer discharge curves, which are available in the battery data sheet [8].

For a single pack 12 V battery, the power can be calculated as $P_{bat} = V_{bat} \times I_{bat}$. For a bulk battery bank such as BES, with power assumed to be uniformly distributed between n_s series connected batteries (string) and n_p parallel connected strings, the total power produced by a battery bank can be calculated by using,

$$P_{BES} = V_{BES} \times I_{BES} = n_s V_{bat} \times n_p I_{bat} \tag{4}$$

Here, n_s determines the total output terminal voltage, whereas n_p characterizes the capacity or total size of a battery bank in kWh.

3.2. Improved BES SOC feedback control method

As in Fig 1, using the signals, P_{PV} and P_{SET} as inputs, the SOC feedback controller is used to generate the BES reference power, $P_{BES,ref}$ in the outer control loop. Figure 2 shows the SOC feedback control scheme developed for hourly PV dispatch strategy, which is improved based on the conceptual design for wind power output smoothing in [9].

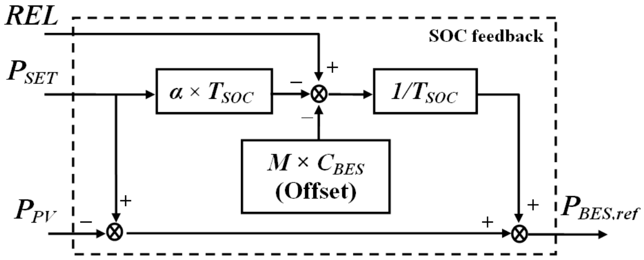


Fig. 2. SOC feedback controller for generating BES reference power (d-axis component).

In this SOC feedback loop, the target is to output the reference signal for charge/discharge of battery power while meeting all the required BES operational constraints. Here, the SOC is varied at a required range during operation by controlling the remaining energy level (*REL*) defined as:

$$REL = C_{BES} - \int P_{BES} dt \tag{5}$$

where C_{BES} is the BES capacity.

The *REL* becomes the feedback signal to the controller and the variation of *REL* (i.e SOC) depends on the control parameters, namely, the time constant, T_{SOC} and the SOC margin rate denoted as M as shown in Fig 2. The offset signal, *offset*= $M \times C_{BES}$ allows a user to specify the percentage of BES energy to be used for regulation. To ensure the target output variation remains within the BES rated capacity, the $\alpha \times T$-fold waveform is applied to the P_{SET} signal, where α is the coefficient defined as follows [9]:

$$\alpha = \frac{C_{BES}(1-2M)}{T \times P_{PV,rated}} \tag{6}$$

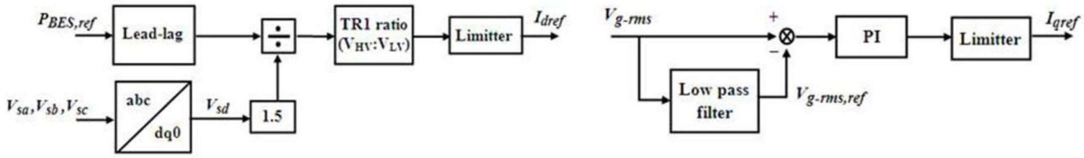
where, $P_{PV,RATED}$ is the rated capacity of the PV farm.

This implies that when *REL* is at a high level, $\alpha \times T$-fold will adjust the BES output to discharging direction, and vice-versa when *REL* is at its lower level. The output signal from the SOC feedback controller, $P_{BES,ref}$ later will be used to generate the d-axis reference current component as:

$$I_{dref} = \frac{2}{3} \frac{P_{BES,ref}}{V_{sd}} \tag{7}$$

where V_{sd} is the d-axis component of BES terminal voltage at PCC.

For the q-axis current component, the grid RMS voltage at PCC is smoothed out at a required level using the washout filter [1]. The difference between the filtered voltage, $V_{g\text{-}rms,ref}$ and the actual voltage, $V_{g\text{-}rms}$ becomes the reference signal for the outer q-axis control loop (I_{qref}). Figure 3 shows the block diagrams for generating d and q-axis reference current components at the outer control loops of the VSC, respectively.The generated d and q current components become input to the inner current control loop (see Fig 1). Further details on the derivation of current control loop may be referred in [10].



(i) (ii)

Fig.3. Generation of battery reference current component for (i) *d*-axis and (ii) *q*-axis.

3.3. Optimal control parameter tuning using GA

For PV hourly dispatch strategy, the control parameters need to be tuned according to the BES size. Considering all the operational constraints for the BES, an optimal control parameter tuning is developed using GA as shown in Fig 4. As in Fig 4, the selected parameter set is located in search space that is the co-ordinate of the controller setting value. GA then generates the initial size, i.e, number of strings. The PSCAD/EMTDC program runs and solve the networks according to the controller set values where the aggregated objective function, *OF(x)* which is the weighted sum of partial objective functions, $of_i(x)$ is evaluated and then returned the optimized values to search for the next point to be investigated. The execution of the program continues until a specified tolerance for *OF(x)* minimization is met. Once the optimized parameters are obtained, the BES converter controller uses the values.

Here, for optimizing the control parameters of the SOC feedback controller and evaluating optimal size of BES, the GA multi-objective optimization considers the following objective function:

$$of(x) = \int_0^{T_1} t\left|P_{BES} - P_{BES,ref}\right| dt + \int_0^{T_2} t\left|V_{BES} - V_{BES,ref}\right| dt \tag{8}$$

where, vector x are the SOC feedback control parameters (T_{SOC} and M) and the battery strings, n_p, respectively. Time, t is selected as 1 s, whereas T_1=3600 s as the P_{SET} changes in every one hour, while T_2=43200 s as V_{BES} is changed over the entire day (12 hours of daytime) of simulation. From (8), the goal is to optimize the control parameters so that the total injected power from BES and PV will follow the hourly dispatched set point provided by the forecasting tools.

The optimization problem is subjected to the operational constraints described as follows:

- The maximum SOC operable range is 70% of total capacity, where SOC_{min} (assumed as depth of discharge (DOD) level is at 30% level)
- For the considered power converter ratings for VSC with IGBT valves, the maximum charge/discharge current should not exceed ± 1 × C A. As the current limitation is specified in the limiter block, every generation with n_p number of strings will block ± n_p × 4/1000 kA of current (case of 12 V 4 Ah battery pack).
- The terminal voltage at the DC-link of the BES is approximately 600 V which is the sum of 50 series (n_s) number of batteries. In determining the minimum battery bank terminal voltage, it is assumed that the maximum charge/discharge current should not exceed 1 × C rate per battery. Therefore, the terminal voltage per 12 V battery pack should not exceed 9.3 V [8]. This value is equivalent to 465 V of the considered BES.

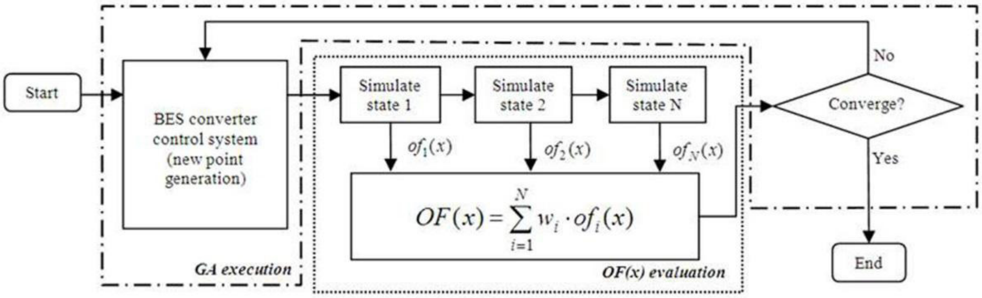
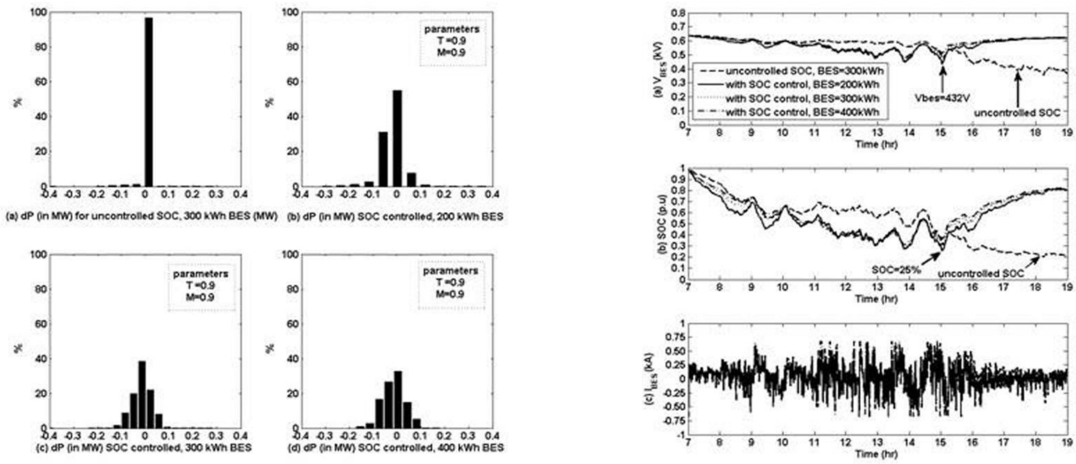


Fig. 4. Flowchart of GA-based control parameters and BES sizing optimization.

4. Simulation results and discussion

4.1. Effects of SOC controller and sizing to the dispatching performance

The dispatching performance with/without SOC controller and the effects of BES sizing selection are evaluated. Deviation of P_{TOTAL} to P_{SET} (dP) is measured to compare the overall performance of the different studied cases. Figure 5-i shows the dP histograms for comparing the performances without deployment of SOC controller (Fig 5-i(a)) and with SOC controller for different BES sizes (Fig 5-i(b)-(d)). Fig 5-ii illustrates how SOC controller with different sizes of BES affects the terminal voltage, SOC and current limit operation of the BES. From Fig 5-i(a)-(d), the percentage of occurrences of unacceptable deviations is compared for each case. For example, if up to ±0.1 MW is assumed as acceptable deviation, the results with SOC controller show that the 200 kWh, 300 kWh and 400 kWh BES have unacceptable deviations of approximately 6.2%, 5% and 5.2%, respectively. Inadequate sizing for the case of 200 kWh BES causes limited allowable maximum charge/discharge current as only up to 1 × C is allowed for each case. Therefore, it causes many spikes to occur due to block in BES current. For the 300 kWh and 400 kWh BES, there is no major difference in the performance and therefore the 300 kWh is considered as optimum size for the case with SOC controller. On the other hand, if the operable range of SOC is uncontrolled, nearly perfect dispatch can be achieved as evident in Fig 5-i(a). However, it is important to note that, uncontrolled SOC causes violation to the SOC limits and operation at terminal voltage exponential region, which in long term may result in subsequent failure to the batteries such as shorter lifetime and premature failure.



(i) (ii)

Fig.5. Effects of SOC controller deployment. (i) Comparison of dispatching performance with/without SOC controller and different sizes of BES. (ii) BESterminal voltage, SOC and current profiles during dispatching operation

As Fig 5-ii(a) indicates, for the case of uncontrolled SOC, it is evident that the terminal voltage for the 300 kWh BES easily hits the lowest terminal voltage limit of the BES, that is 465 V. Similarly, in Fig 5-ii(b), the SOC also exceeds the lowest DOD limit that is assumed at 30% of the total BES capacity. Therefore, in practice SOC needs to be properly controlled so as to meet the acceptable dispatching performance with adequate size of BES.

With controlled SOC, the sizes of BES have to be carefully selected to ensure all the operational constraints meet the specified criteria. For a controlled SOC, the operable range of SOC is not violated and the controller keeps the SOC within 70% of the total capacity as evident in Fig 5-ii(b). However, inadequate size selection, for the case of the 200 kWh BES, the terminal voltage and SOC exceeds the limitations defined in Section 3.3, which are 432 V and 25%, respectively. The 300 kWh BES with controlled SOC is considered optimal for the case of considering the SOC control parameters, T=0.9 and M=0.9. Although using the 400 kWh BES improves the terminal voltage and SOC operation range as compared to the 300 kWh, however, the overall dispatching performance remains the same.

4.2. Optimal SOC control parameters and BES size

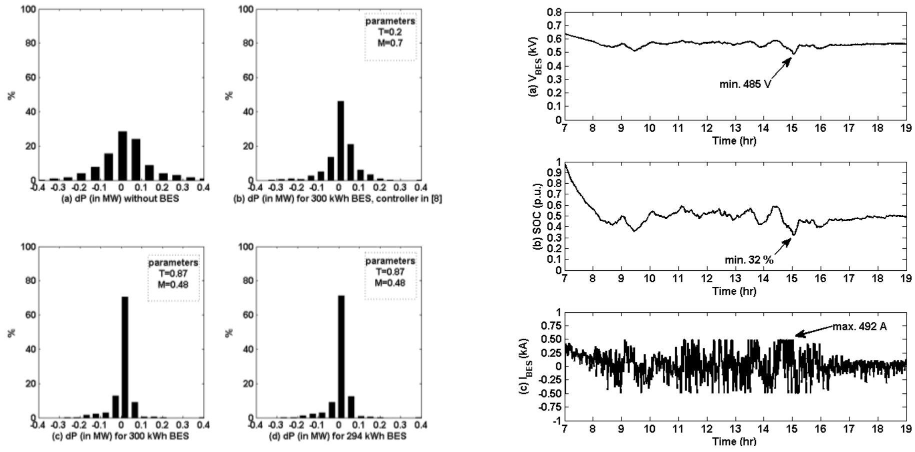
Using GA, the optimal values for the SOC control parameters, T_{SOC} and M and size of BES are obtained by evaluating n_p. Table 1 shows the results of the optimization problem based on 1000 runs. For comparison purpose, the parameter values of the SOC controller in [3] are also given.

Table 1. GA optimized parameter values.

	Proposed SOC controller		
Parameter	Operating range	Optimal value	SOC controller in [3]
Time constant, T	$0.1 \le T \le 0.9$	0.87	0.2
SOC margin rate, M	$0.3 \le M \le 0.9$	0.48	0.7
BES strings, n_p	$115 \le n_p \le 135$	122.5 (294 kWh)	125 (300 kWh)
OF(x)	0.7484 (initial)	0.4147 (optimized)	-
Operational constraints	465 V $\le V_{BES} \le$ 635 V, 30% $\le$ SOC $\le$ 100%, $\pm I_{BES}$ maximum 1 × C Amps		

From Table 1, with the operational constraints specified in the SOC controller design, optimal parameters have been found at T_{SOC} = 0.87 and M = 0.48, respectively. In addition, with improved dispatching performance using new parameter sets, the optimal size for BES is found at 122.5 numbers of strings (approximately 294 kWh) which gives 2% reduction from the initially estimated size of 300 kWh. Comparing the performance, it is evident from Fig 6-i(a) that if BES is not used to smooth out the P_{PV} output and dispatch on an hourly basis, the unacceptable deviation, which is the deviation that exceeds ± 0.1 MW is found to be approximately 31.6%. However, with SOC controller employed, the unacceptable deviations are greatly improved to less than 15% as shown in Fig 6-i(b)-(d). Furthermore, the proposed optimal SOC control method improves the performance compared to the controller in [3] from 14.5% to about 4.5% unacceptable deviation. Figure 6-i(d) also shows that BES size is reduced to 294 kWh that is approximately 2% smaller than the initially estimated 300 kWh with equal dispatching performance of Fig 6-i(c).

With the acceptable performance using the optimal parameters and size of BES as shown in Fig 6-i(d), the resulting terminal voltage, SOC and current profiles of the BES are also shown as in Fig 6-ii, respectively. From the figure, all the operating constraints specified for the VSC converter are within its operable range. The lowest terminal voltage is measured at 485 V, while SOC is allowed to vary within 70% of total capacity. For the 294 kWh BES, the maximum allowable charge/discharge current (1 × C) is 492 A. With proper control of BES operational constraints for this application, this type of battery (VRLA) can be charged/discharged up to typically 5 years [8] depending on average depth of discharge considered. However, other than low cost VRLA-type batteries, the proposed SOC controller is also applicable for higher efficiency batteries such as lithium and nickel-type which have greater SOC operable range and high charge/discharge rate.



(i) (ii)

Fig.6. Optimal SOC controller performance. (i) Comparison of dispatching performance for the case without BES and BES with optimal SOC control scheme. (ii) BES terminal voltage, SOC and current profiles for the case of BES size 294.

5. Conclusion

A new strategy is presented to mitigate the intermittent cloud effects and varying input temperature of a large PV system by smoothing and hourly dispatching the net output power using BES. An optimal feedback control method for BES SOC is proposed using the GA-based multi-parameter optimization to improve the dispatching performance while meeting the required operational constraints for BES. Based on the performance analysis results for the different cases considered, the proposed optimal controller is found effective. Furthermore, optimal BES size is also obtained using the proposed GA-based optimization that is around 2% reduction compared to the initially estimated size. This work facilitates the requirement for optimal SOC control strategy and size for BES to smooth out fluctuation and dispatching the PV output on an hourly basis particularly for the case of Malaysia.

References

[1] Han C, Huang AQ, Baran M, Battacharya S, Lintzengerger W, Anderson L, Edris AA. STATCOM impact study on the integration of a large wind farm into a weak loop power system, IEEE Transactions on Energy Conversion 2008;23:226-233.

[2] Omran WA, Kazerani M, Salama MMA. Investigation of methods for reducing of power fluctuations generated from large grid-connected photovoltaic systems, IEEE Transactions on Energy Conversion 2011;26:318-327.

[3] Teleke S, Baran ME, Huang AQ, Bhattacharya S, Anderson L. Control strategies for battery energy storage for wind farm dispatching, IEEE Transactions on Energy Conversion 2009;24:725-732.

[4] Teleke S, Baran ME, Battacharya S, Huang AQ. Rule-based control of battery energy storage for dispatching intermittent renewable sources, IEEE Transactions on Sustainable Energy 2011;1:117-124.

[5] Teleke S, Baran ME, Bhattacharya S,Huang AQ. Optimal control of battery energy storage for wind farm dispatching, IEEE Transactions on Energy Conversion 2010;25:787-794.

[6] ENFOR. Forecasting and optimization for the energy sector 2012, Available: http://www.enfor.dk/index.php

[7] Tremblay O, Dessaint LA, Dekkiche AI. A generic battery model for the dynamic simulation of hybrid electric vehicles, IEEE Vehicle Power and Propulsion Conference 2007.p.284-289.

[8] Yuasa. Yuasa NP valve regulated lead-acid battery manual 1999, Available: http://www.yuasaeurope.com/en-gb/industrial/products/np/

[9] Yoshimoto K, Nanahara T, Koshimizu G, Uchida Y. New control method for regulating state-of-charge of a battery in hybrid wind power/battery energy storage system, IEEE Power Engineering Conference and Exposition 2006.p.1244-1251.

[10] Daud MZ, Mohamed A, Wanik MZC, Hannan M A. Performance evaluation of grid-connected photovoltaic system with battery energy storage, IEEE International Conference on Power and Energy 2012.p.396-401.